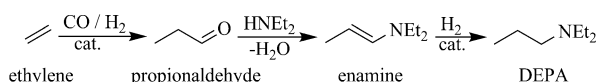


Supported Catalysts

Continuous Gas-Phase Hydroaminomethylation using Supported Ionic Liquid Phase Catalysts**

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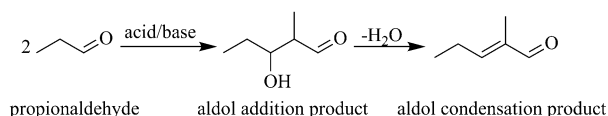
The term hydroaminomethylation refers to a one-pot cascade reaction of an alkene hydroformylation followed by reductive amination. Because water is the only byproduct, this reaction sequence represents an atom-efficient, elegant way to produce amines. Scheme 1 shows the hydroaminomethylation sequence for ethylene, hydroformylation followed by reaction with diethylamine to form *N,N*-diethylpropan-1-amine (DEPA) through an enamine intermediate.



Scheme 1. Hydroaminomethylation of ethylene using diethylamine as the amine component.

Despite the fact that the hydroaminomethylation sequence was first described by Reppe and Vetter already in 1949,^[1,2] extensive research in this field has only taken place in recent years.^[3–5] From this work it is evident that a major challenge in hydroaminomethylation is to realize high chemoselectivity, in particular to suppress aldol condensation of the aldehyde intermediate (Scheme 2).

Hydroaminomethylation has been shown to work even with unmodified rhodium catalysts, although with moderate selectivities.^[6] In 1999, Beller and co-workers^[7] reported on



Scheme 2. Aldol condensation of propionaldehyde.

TPPTS- and BINAS-modified rhodium complexes in the hydroaminomethylation using ammonia as the amine substrate. A dual-metal catalyst (Rh, Ir) and a liquid–liquid biphasic reaction system (water, MTBE) were applied in this work. Besides the desired primary amine product, secondary amines, tertiary amines, imines, enamines, and aldol condensation products were formed. Later, the same group obtained much better selectivities using Rh-IPHOS^[8] and Rh-Xantphos-systems.^[9,10] For the hydroaminomethylation of terminal, aliphatic olefins, very high *n/iso* ratios of the product amines could be realized (*n/iso* > 98:2). Beller and co-workers also investigated the hydroaminomethylation of 1-octene in supercritical ammonia and found yields for primary nonylamine of up to 60 % under optimized reaction conditions.^[11]

Ionic liquids (ILs) were first applied in the hydroaminomethylation by Eilbracht and co-workers,^[12] who patented the use of ionic liquids to recycle unmodified rhodium and iridium catalysts. More recently, Vogt and co-workers^[13] reported on the hydroaminomethylation of long-chain (C_6 – C_{12}) olefins with piperidine as the amine substrate using a liquid–liquid biphasic reaction system with Rh/Sulfoxantphos in 1-methyl-3-pentylimidazolium tetrafluoroborate [C_5mim][BF_4] as the IL phase.^[14] The results were compared with toluene/MeOH and a significant decrease in side-product formation was found in the IL system.

Herein, we describe catalytic hydroaminomethylation in a continuous gas-phase reaction using supported ionic liquid phase (SILP) materials as microscopically homogeneous but macroscopically heterogeneous catalysts. Within SILP catalysts, a thin IL film creates a uniform solvent environment for the dissolved transition-metal complex,^[15] while the highly porous solid on which this ionic catalyst solution is supported creates a high gas–liquid interfacial area for fast mass transport (Figure 1).^[16,17] Product/catalyst separation takes place in the system by evaporation of the products from the

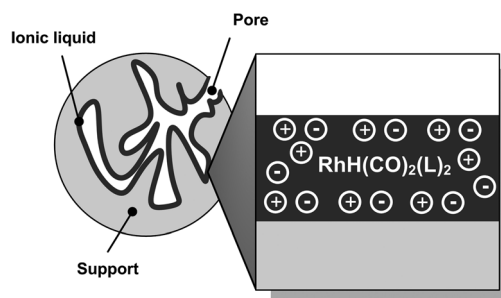


Figure 1. Schematic view of a supported ionic liquid phase (SILP) catalyst system.

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ionic catalyst phase making use of the extremely low vapor pressure of the latter. SILP systems have been successfully applied in various gas-phase catalytic applications^[18] and recently, even for reactions with complex selectivity requirements, such as asymmetric hydrogenations.^[19] Herein, we introduce the possibility of SILP tandem reactions as the formation of the desired amine requires a sequence of selective hydroformylation, enamine formation, and enamine hydrogenation in one gas-contacted catalyst bed.

The hydroaminomethylation of ethylene with synthesis gas ($H_2/CO = 2:1$) and diethylamine (Scheme 1) was investigated using $Rh(acac)(CO)_2$ and Xantphos (4,5-bis(diphenylphosphino)-9,9-dimethylxanthene) as a phosphine ligand ($L/Rh = 5:1$). Silica 100 was applied as a porous solid support and the first experiments were performed without any ionic liquid to establish a baseline comparison of the purely physisorbed catalyst. This purely physisorbed Rh-Xantphos catalyst on silica showed high hydroformylation activity ($X_{ethylene} = 84\%$, $TOF = 500\ h^{-1}$; for details see the Supporting Information) owing to the fact that the reaction products remain as liquids in the pores by capillary forces and provide the solution phase for the working homogeneous catalyst. Consequently, an activation period during the first hours of the experiment is observed, which is attributed to the development of a high boiling liquid layer of side-products in the pores. However, the reductive amination step rarely took place and the yield in the desired DEPA faded out completely over time (see Supporting Information for details). The majority of the intermediate propionaldehyde readily reacted in an aldol side reaction (Scheme 2) to form the aldol adduct ($Y_{aldol\ add} = 50\%$) and aldol condensation product ($Y_{aldol\ cond} = 16\%$, only traces of hydrogenated aldol condensation product were found) leading to very low propionaldehyde concentrations ($Y_{propional} = 15\%$) in the mixture analyzed at the reactor outlet. The observed catalytic activity was only obtained in the presence of the Xantphos ligand and even Rh/ligand ratios of less than or equal to two led to inactive systems.

We further investigated the influence of different ionic liquid coatings (Figure 2) on the catalytic performance of the Rh-Xantphos catalyst. Because ILs can be tuned through the combination of cations and anions,^[20] we examined SILP

catalysts with ILs of different hydrophobicities and basicities (Table 1, for detailed data see Supporting Information). The selectivity and activity of the hydroaminomethylation was strongly influenced by the nature of the IL applied in the

Table 1: Hydroaminomethylation of ethylene and diethylamine with SILP catalysts in a continuous gas-phase reaction—influence of different ionic liquid coatings.^[a]

Ionic Liquid	X [%]	TOF [h^{-1}] ^[c]	Yield [%] ^[b] propanal	aldol prod.	DEPA
None	84	500	15	66	2
[EMIM][OAc]	74	519	21	52	0
[EMIM][OTf]	60	406	20	24	14
[MMMIM][NTf ₂]	51	351	13	2	35
[OMIM][NTf ₂]	76	549	7	40	28

[a] Reaction conditions: 120 °C, 10 bar, $L = Xantphos$, $L/Rh = 5:1$, 0.2 wt % Rh, Silica 100, α_{IL} (pore filling degree) = 0.1, 2.5 g SILP catalyst, gas flows are given in milliliter per minute under standard conditions ($NmL\ min^{-1}$) 200 $NmL\ min^{-1}\ H_2$, 100 $NmL\ min^{-1}\ CO$, 10 $NmL\ min^{-1}\ ethylene$, 1 $g\ h^{-1}$ diethylamine, residence time = 8.4 s. Values after 20 h time-on-stream.

[b] Determined by GC (enamine, alcohols, and higher boiling aldol condensation products were less than 1 %). [c] Turnover frequency in [$mol_{ethylene} (mol_{Rh}^{-1} h^{-1})$].

SILP material. The IL-dissolved Rh-Xantphos catalyst switched from the production of only aldol condensation products for the basic IL [EMIM][OAc] ($S_{DEPA} < 0.5\%$) to high combined selectivities for hydroformylation and reductive amination in the case of [MMMIM][NTf₂] ($S_{propanal+DEPA} > 94\%$). With the latter IL coating the catalyst activity was somewhat lower than with [OMIM][NTf₂] indicating a beneficial effect of higher IL lipophilicity on the reaction rate. However, with [OMIM][NTf₂] the formation of aldol products increased over time-on-stream from 7 % after two hours to 40 % after 20 hours. This can be attributed to the accumulation of DEPA and high-boiling basic side products in the IL film, leading to an increase in basicity of the ionic catalyst solution and thus to enhanced aldol formation. All catalytic results confirm that the formation of the desired DEPA benefits from ILs carrying anions of low basicity and cations of low lipophilicity.

Further experiments were done to optimize the support material of the SILP hydroaminomethylation catalyst. Because a detrimental influence of IL basicity on DEPA selectivity was clear from the IL variation experiments, we expected similar effects for the support (Table 2). Indeed, variation of the support confirmed that SILP materials based on neutral oxidic supports showed less aldol formation than using the slightly basic support Pural TH 60. The highest DEPA selectivity was achieved on the highly porous carbon support PBSAC (PBSAC = polymer-based spherical activated carbon; Figure 3, $S_{DEPA} > 99\%$). The fact that the PBSAC support shows high basicity in the PZC measurement indicates that the simple relation between support basicity and aldol formation seems to only hold true for a comparison of different oxidic supports.

To demonstrate the long-term stability of the developed hydroaminomethylation catalyst we operated the Rh-Xantphos-SILP system with the IL [MMMIM][NTf₂] on the

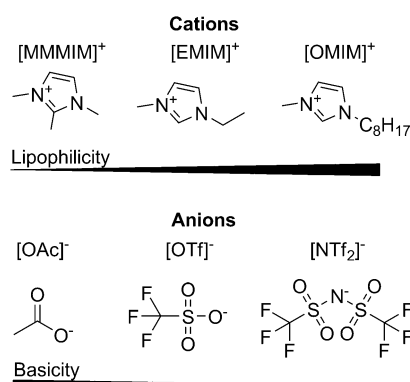


Figure 2. Order of lipophilicity and basicity of the cations and anions used in this study.

Table 2: Continuous gas-phase hydroaminomethylation of ethylene and diethylamine using SILP catalysts (Rh-Xantphos in [MMMIM][NTf₂])—influence of different support materials.^[a]

Support (PZC) ^[b]	X [%]	TOF [h ⁻¹]	Yield [%] ^[c] propanal	aldol prod.	DEPA
Silica 100 (6.38)	51	351	13	2	35
Pural TH 60 (7.95)	32	219	13	8	10
AlOx neutral (7.69)	22	144	5	1	15
PBSAC ^[d] (11.3)	72	520	2	0	70

[a] Reaction conditions: 120 °C, 10 bar, L = Xantphos, L/Rh 5:1, 0.2 wt % Rh, IL = [MMMIM][NTf₂], α_{IL} = 0.1, 2.5 g SILP catalyst, 200 NmL min⁻¹ H₂, 100 NmL min⁻¹ CO, 10 NmL min⁻¹ ethylene, 1 g h⁻¹ diethylamine, residence time = 8.4 s. Values after 20 h time-on-stream. [b] PZC = point of zero charge; PZC values were measured to compare the acidity of the support (see Supporting Information for details). [c] determined by GC (enamine, alcohols, and higher boiling aldol condensation products were less than 1%). [d] 2 g h⁻¹ diethylamine.

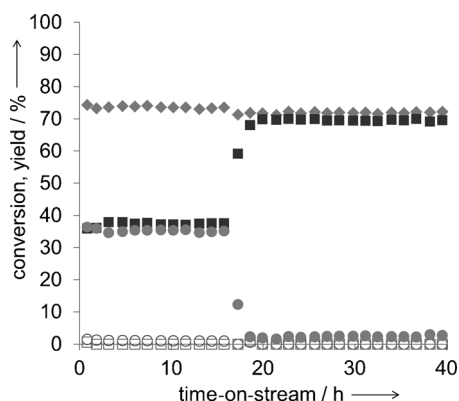


Figure 3. Hydroaminomethylation of ethylene and diethylamine with SILP catalyst (Rh-Xantphos in [MMMIM][NTf₂] on PBSAC support). Conversion of ethylene (◆), yield of aldol adduct (□), yield of aldol condensation product (○), yield of propionaldehyde (●), yield of DEPA (■)—Reaction conditions: 120 °C, 10 bar, L = Xantphos, L/Rh 5:1, 0.2 wt % Rh, PBSAC, α_{IL} = 0.1, 2.5 g SILP catalyst, 200 NmL min⁻¹ H₂, 100 NmL min⁻¹ CO, 10 NmL min⁻¹ ethylene, 0–17 h; 1 g h⁻¹ diethylamine, 17–40 h; 2 g h⁻¹ diethylamine, residence time = 8.4 s.

PBSAC support for more than 18 days time-on-stream reaching a total turnover number of 115 000. [NTf₂]⁻ based ionic liquids are particularly suitable for such long-term testing, because these hydrophobic ILs are characterized by high stability against thermal decomposition and hydrolysis.^[21] After a slight initial deactivation (by approximately 20%), the catalyst activity remained almost stable during this extended period at a level of TOF = 450 h⁻¹ with an average DEPA selectivity of more than 99% (for details see the Supporting Information). No formation of aldol side products and enamines was observed during the entire time of operation. During the long-term experiment, the product condensate was analyzed for traces of Rh, phosphine, and ionic liquid by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Gas-phase leaching was found to be negligible, with all relevant elements remaining below the detection limit of 2 ppm.

In conclusion, we have demonstrated that SILP materials are suitable catalyst materials for the continuous gas-phase

tandem reaction of hydroformylation, amination, and enamine hydrogenation using Rh-Xantphos complexes as the immobilized homogeneous catalyst. Interestingly, the main effect of the ionic liquid solvent (compared to reaction of the Rh-complex dissolved in supported aldol products in the absence of the IL; Table 1) is on the competition between the desired amination/hydrogenation and the undesired aldol condensation. While the IL-free system and the SILP systems with a basic acetate coating form almost exclusively aldol condensation products from the initial hydroformylation product propanal, SILP catalysts based on neutral oxide and porous carbon supports and ILs of low basicity and lipophilicity result in very selective hydroaminomethylation catalysis. The long-term stability of the developed systems is remarkably high and this highlights the potential of these SILP catalysts for future applications in industrial amine production.

Experimental Section

SILP catalysts were prepared by impregnation under argon atmosphere using standard Schlenk techniques. A solution of Rh-(acac)(CO)₂ (0.0144 g, 0.056 mmol) and Xantphos (4,5-bis(diphenylphosphino)-9,9-dimethylxanthene; 0.162 g, 0.28 mmol) in dichloromethane was stirred for 20 min and the respective amount of ionic liquid (0.36–0.42 g) equal to α_{IL} = 0.1 ($\alpha_{IL} = V_{IL}/V_{pore}$) was added. Finally, 2.86 g of the support calcinated Silica 100 (pore volume V_{pore} = 0.98 mL g⁻¹, BET surface area = 358.9 m² g⁻¹), Pural TH 60 (V_{pore} = 0.60 mL g⁻¹, BET surface area = 325.63 m² g⁻¹), AlOx neutral (V_{pore} = 0.28 mL g⁻¹, BET surface area = 1358 m² g⁻¹), or activated carbon (PBSAC from Blücher; V_{pore} = 1.18 mL g⁻¹, BET surface area = 2005 m² g⁻¹) was added and the suspension was stirred for another 10 min before the solvent was slowly removed under reduced pressure at 40 °C. The continuous gas-phase hydroaminomethylation experiments were conducted at 120 °C and 10 bar pressure using a fixed bed reactor set-up. The gaseous feedstocks (H₂ 200 NmL min⁻¹, CO 100 NmL min⁻¹) were fed by mass flow controllers (MFC) and ethylene (10 NmL min⁻¹) through a mini coriolis flow (mini CORI) from Bronkhorst. Liquid diethylamine (1–2 g h⁻¹) was pumped through an HPLC pump (Techlab) and fed into a controlled evaporator and mixer (CEM) from Bronkhorst, where it was evaporated. The gaseous feed stream led to a reactor of 30 cm³ volume where a fixed bed of SILP material (2.5 g) catalyzed the reaction with a residence time of 8.4 seconds. The product feed stream was continuously analyzed by a DANI Master GC equipped with an FID detector. All gas flow meters and the GC were calibrated prior to use. Additional experimental details can be found in the Supporting Information.

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